Strategy for increasing the energy in 1999

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Abstract

The implications for the RF system from operating the LEP superconducting accelerating cavities at higher gradients will be presented, together with a scenario for the evolution of the beam energy during 1999. The question of the necessary RF reserve and consequences for stable operation will be addressed.

1. INTRODUCTION

During the two remaining years of LEP operation the beam energy will be increased to the very maximum, still allowing stable operation for good integrated luminosity. In 1998 reliable performance has been achieved with the superconducting cavities running at or near their design gradient of 6 MV/m. Adequate reserve in circumferential voltage was available, allowing to keep the beam circulating even in case of two klystrons tripping. In order to reach energies near 100 GeV the accelerating gradient in the superconducting cavities has to be increased substantially above its design value. In this paper possibilities and constraints for reaching high gradients are shown and a scenario for increasing the beam energy during 1999 is proposed.

1. PREPARATIONS FOR RUNNING AT HIGHER GRADIENTS IN 1999

In other contributions [1] the ongoing work on the LEP RF system and the cryogenic installation as well as improvements implemented during the last year are described, which are necessary in order to increase the cavity gradient, improve the reliability of the overall RF system and to remove limitations both on fields as well as on beam current. This concerns both hardware and software.

1.1. Increasing the average gradient

In order to reach the highest possible average gradient, a programme is under way to equalise the fields in cavities fed by one klystron, the main features of which are: Differences in Q_{ext} are corrected by impedance transformers in the waveguides and beam induced asymmetries are reduced by careful adjustment of electrical waveguide lengths and phases.

Several methods are possible to condition the cavities and their accessories to higher gradients: Standard conditioning based on vacuum and radiation, pulsed power conditioning and He processing. The last method will have to be limited to few cavities, considering the risks involved and the time required.

Based on previous experience we aim to reach an average gradient during conditioning of **7.2 MV/m.** The operationally usable gradient will be somewhat lower. The contractual design gradient during cavity fabrication was 6 MV/m at a Q_0 value of $3.2*10^9$. The radiation level at these gradients has to be acceptable, around 10 kRad/hour.

1.2. Constraints

The work load during the 1998/1999 shut-down is considerable: An important upgrade project of the cryogenic plants is under way; four new cavity modules are being installed with over 100 m long waveguide stretches including ferrite phase shifters, and have to be commissioned; all antenna cables inside the cryostat are being replaced, etc. Therefor the time for conditioning will be rather limited at the end of the shutdown.

The maximum gradient which the cavities will reach by in situ conditioning alone is uncertain. There is no time before 1999 operation to remove limiting cavities from the LEP ring for offline treatment of the Nb films.

2. LIMITS FOR GRADIENT

As is shown in the other contributions to this session, many known performance limits have been removed. In this chapter some of the remaining constraints are discussed.

2.1. Radiation

The aim of cavity conditioning is the reduction of field emission and the associated dark current. The usable gradient is given by the acceptable level of field emission. This can be monitored by measuring the radiation generated in the cavities. It is impossible at this time to define a hard limit with precision. The danger from running at very high radiation levels comes from potential damage of the superconducting layer through emitters or impinging electrons. Some damage through heating of the conical transition pieces at the extremities of the modules has already been observed. Radiation damage of materials in or around the modules is another risk. The radiation is causing induced radioactivity in cavity components, making interventions more difficult.

Sudden spikes in the pressure of the He bath, with subsequent triggering of the beam dump have been observed as a consequence from running too close to field emission limits.

2.2 Cryogenic power and Q_0-value

The ultimate maximum accelerating gradient is given by the cooling capacity of the cryogenic plant. The power dissipated by a cavity is given by

$$P_{cr} = \frac{E^2}{R/Q * Q_0} + Z * i_b^2 * n$$

P_{cr} is the cryogenic load per cavity, E the accelerating field in a cavity, R/Q = 464 Ω is the characteristic impedance of a cavity, Z characterises the beam related cryogenic power, i_b is the bunch current and n the total number of bunches.

The unloaded Q-value Q_0 can be estimated using an extrapolation of the fabrication specifications ($6.4*10^9$ at low field, $3.2*10^9$ at 6 MV/m) as shown in fig. 1.

$$\log(Q_0) = -0.0502 * E_{acc}[MV/m] + 9.806$$

At 7 MV/m this gives $2.8*10^9$.

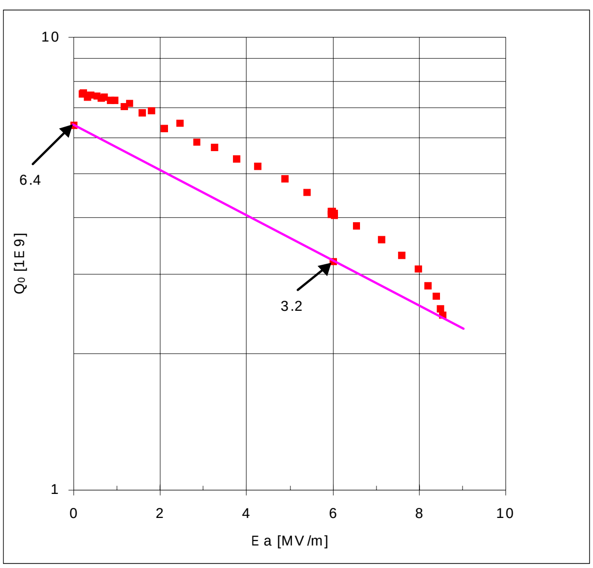

Fig. 1: Proposed extrapolation of Q0 for higher accelerating fields. The dots are measurements on a typical cavity.

Z, the beam dependent impedance is assumed to be 8 MΩ after changing all antenna cables. This gives an ultimate gradient limit due to available cryogenic power:

7.9 MV/m at 0-current,
7.6 MV/m at 8 mA.

The maximum cryogenic power which can be supplied to a single cavity is about 160 W. This is imposed by hardware such as valves and pipework.

It is most likely, that the majority of cavities will not reach the gradients given by the cryogenic limit because they hit other limitations before.

2.3. Stored energy / transients

The stored energy in the electromagnetic fields in a cavity is proportional to E^2. From 6 to 7 MV/m it increases by 36 %. This causes higher transients in reflected power at RF trips, or other fast switch-off. This can give problems especially during conditioning.

3. LIMITS ON BEAM CURRENT

During 1998 the beam current had to be limited because of problems with cables connected to cavity field antenna. The cables on all Cu/Nb modules have been changed during the winter shutdown, therefore this limit should not exist any more. Some other factors potentially limiting the beam current will be discussed in this chapter.

With higher fields and higher currents, the field distribution on the power couplers will be different. Multipactoring might occur, which can not be conditioned during the commissioning time without beam. Conditioning will rather happen during operation with beam, with the bias high voltage applied. We know from past experience, that this can lead to potentially dangerous big vacuum outbursts. It is therefore advisable to raise the current gradually.

The beam dependence of the cryogenic load is shown in the previous paragraph. The impact on maximum gradient and beam current, however, is small.

In the past we had problems with ponderomotive cavity oscillations, which depend on the total circulating beam current. For next year a new damping system, which has been shown to work in most cases, is being developed and built. The system is foreseen to become available during the year and will be introduced gradually. Setting up is rather lengthy. If this system proves to work everywhere, the problem with ponderomotive oscillations should become much less important.

During 1998 some High Order Mode (HOM) couplers showed regular temperature rises in the presence of beam, the origin of which is not understood yet. In one case at least the temperature increase was associated with a quench of an HOM coupler, an additional power of 100 W was deposited into the cryogenic system. With higher currents, such phenomena are expected to become more frequent.

4. LIMITATIONS ON BUNCH LENGTH

Since the antenna cables are being replaced during the 1998/1999 shut down, the major limitation on bunch length should also disappear. In this paragraph some issues are mentioned, which should be kept in mind, if one wants to operate at less than 10 mm bunch length.

All these points do not impose a strict limit, but it seems advisable, not to jump too quickly to very short bunches.

Only antennas on Nb sputtered cavities are being replaced in situ. No such procedure for the solid Nb cavities exists up to now. The cables, however follow a different path through the super insulation than the damaged ones. They have been checked by reflectometry, and found not to be damaged so far.

The beam induced cryogenic load increases strongly with decreasing bunch length [2].

The shielded vacuum bellows in the area of the 1 GHz cavities for longitudinal feedback heat up during beam operation. Up to 200 °C have been measured [3]. This is believed to come from higher order modes excited by the beam in the 1 GHz cavities. Modes above cut-off of the beam hole can leave the cavities, travel along the beam pipe and heat the bellows shielding. The loss factor for these cavities increases strongly with shorter bunches.

5. GENERAL PERFORMANCE ASPECTS

This chapter lists some aspects which might affect performance and reliability.

In previous years the solid Nb cavities always reached average gradients of 5 MV/m after conditioning. In some cases the gradient had to be reduced during operation with beam, because too many spurious beam dumps occurred, caused by a sudden He pressure rise in these cavities.

	Nr cav's	grad [MV/m]	total MV	
After commissioning, with the same performance as in 98 we expect:				
Cu	48		100.0	
Solid Nb	16	5	136.0	
Cu/Nb	272	6	2774.4	
		nominal sum	**3010.4**	
		efficiency %	96	
		1 klystron down	-81.6	
		2 klystrons down	-163.2	
available	**2808 MV**			**96.7 GeV**
	2727 MV			**96 GeV**
After stable operation is achieved, rise the gradient in Cu/Nb cavities to 6.5 MV/m:				
Cu	48		100.0	
Solid Nb	16	5	136.0	
Cu/Nb	272	6.5	3005.6	
		nominal sum	**3241.6**	
		efficiency %	96	
		1 klystron down	-88.4	
		2 klystrons down	-176.8	
available	**3024 MV**			**98.6 GeV**
	2935 MV			**97.8 GeV**

Table 1: Available voltage and energy for different gradients. The values given in the boxes are for one klystron down

After the upgrade of the cryogenic plants, the He pressure will be increased from 1300 mbar to 1400 mbar, leading to a temperature rise of 0.13 K. This reduces the Q-value by about 8%. The tuning will work at a different reference temperature. Tests, which could, however, only be done on one unit, have shown that the tuning range is still sufficient.

The klystron power is limited by the modulator settings to 850 kW at a klystron voltage of 82 kV. If more RF power is required, a hardware intervention is necessary.

6. STRATEGY FOR ENERGY INCREASE

The total circumferential fields are shown in table 1.

In the first part the nominal gradient of 6 MV/m is assumed. The useful energies with an efficiency of 96% are 96.7 GeV and 96 GeV for one or two klystrons down respectively. This corresponds to the same performance as last year. The second part of the table shows the conditions if the gradient can be raised to 6.5 MV/m. Under the same conditions as before, 98.6 GeV can be reached with one klystron off and 97.8 GeV with two klystrons off.

The required gradients to achieve 100 GeV are shown in table 2, with different scenarios of reserve. Again for an availability of 96 % an average gradient of 6.9 MV/m is required for one klystron off. If two klystrons are down, the gradient required is 7.1 MV/m.

	Nr cav's	grad [MV/m]	total MV	
Cu	48		100.0	
Solid Nb	16	5.0	136.0	
Cu/Nb	272	6.9	3197.0	
		nominal sum	**3433.0**	
		efficiency %	96.0	
		1 klystron down	-94.0	
		2 klystrons down	-188.1	
available	**3202 MV**			**100 GeV**
	3108 MV			**99.3 GeV**
Cu	48		100.0	
Solid Nb	16	5.0	136.0	
Cu/Nb	272	7.1	3301.5	
		nominal sum	**3537.5**	
		efficiency %	96.0	
		1 klystron down	-97.1	
		2 klystrons down	-194.2	
available	**3299 MV**			**100.7 GeV**
	3202 MV			**100 GeV**

Table 2: Required gradients for 100 GeV

The proposed scenario for increasing the energy is:

Soon after commissioning, 96 GeV per beam should be reached with a total beam current of about 5-6 mA. This corresponds to the same performance as last year.

The gradient should then be raised gradually to about 6.5 MV/m during stable physics coasts at this energy, without pushing the beam current higher than 6 mA. Once stable operation at a gradient of 6.5 MV/m is achieved, the energy should be increased to 98 GeV for stable physics coasts.

During physics at 98 GeV the gradient can be increased again, if possible, to the maximum achievable.

According to the reached gradient, the energy can be increased to the maximum.

At top energy the beam current can then be gradually increased.

7. CONCLUSION

Last year's success is due to a realistic accelerating gradient, nevertheless a very big effort was required to maintain the performance.

It is vital, to keep the RF maintenance day.

Energy steps proposed are 96GeV, 98GeV, maximum. Stable running at higher gradients should be achieved at constant energy and about 5-6 mA beam current. Only then should the energy be increased.

In 1999 we will run in a new regime of RF power and cavity gradient. It is not sure, that the availability of 96% can be maintained under these conditions. Stable operation for "reasonable" integrated luminosity might require a safety margin of more than one klystron trip.

"In fact, LEP is the only machine where the operating average accelerating field is so close to the maximum achieved in the laboratory". (Chamonix 1996, D.Boussard)

This statement is still valid today.

REFERENCES

[1] All contributions to session 6, These proceedings

[2] G.Cavallari et al, "Beam related cryogenic load in LEP superconducting modules", CERN SL-MD note 247,1997

[3] Noel Hilleret, private communication